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Link Adaptation Performance Evaluation for a MIMO-OFDM Physical Layer in a Realistic Outdoor Environment

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Abstract—This paper presents a downlink performance analysis of a link adaptation (LA) algorithm applied to a MIMO-OFDM Physical Layer (PHY) which is a popular candidate for future generation cellular communication systems. The new LA algorithm attempts to maximize throughput and adaptation between various modulation and coding schemes in combination with both space-time block codes (STBC) and spatial multiplexing (SM) is based on knowledge of SNR and H matrix determinant; the parameters which are found to have the most significant influences on the system throughput. By means of ray-tracing software, a detailed example coherent time-variant channel trace is generated. Subsequent application of physical layer simulation software to this channel trace yields throughput results for adaptive MIMO-OFDM for the cases of the proposed LA algorithm, an algorithm based on SNR only, an algorithm based on SNR and H matrix determinant with fixed threshold levels for different SM modes and the optimal case.

I. INTRODUCTION

Research on future generation cellular systems has focused on providing higher data rates with increased spectral efficiency and improving coverage and communication reliability by employing multiple antennas at both transmitter and receiver. A MIMO-OFDM system is very promising [1] and its performance can be further enhanced if an LA algorithm [1,2] is adopted. In the absence of multiple antennas, Adaptive Modulation and Coding (AMC) schemes [2] allow different data rates to be assigned to the system depending on the channel conditions. In the case of a MIMO system, the adaptation can be further extended to switch between STBCs [3] for diversity gain and SM [4] for increased transmission rates. The best choice of transmission parameters will vary according to the application requirements and channel conditions. This paper focuses primarily on the case of delay insensitive applications for which maximisation of throughput is the criterion for adaptation, and examines the performance of an adaptive MIMO-OFDM system in a realistic outdoor environment, modeled using ray tracing software.

A sub-optimal LA algorithm based on 2 channel parameters, SNR and H matrix determinant, was proposed in [5] with predefined H matrix determinant threshold levels, and evaluated in terms of its performance over a channel trace generated by considering an example route in a ray-traced (simulated) outdoor environment. This algorithm is referred to as LASD-F (Link Adaptation based on SNR and Determinant – Fixed) in this paper. The throughput performance of LASD-F algorithm was shown in [5] to be much better than one based

on SNR only (referred to in this paper as LAS – Link Adaptation based on SNR). [5] also showed that adjusting the threshold level governed a trade-off between the ability to avoid severe PER (outage) in some channels and the ability to more closely track the optimal throughput in others. This paper proposes a new LA algorithm referred to as LASD-V (Link Adaptation based on SNR and Determinant – Varying) with further throughput and error performance improvement. No fixed H matrix determinant threshold level is needed for LASD-V, and the SNR thresholds are no longer fixed but vary with the change of H matrix determinant. Compared to [5], this paper also extends the analysis to test the different LA algorithm in a new route with medium level of SNR, which results in the need for the LA algorithm to switch among different PHY modes more frequently and therefore provides a more challenging test of the capabilities of the algorithms.

II. PHY AND CHANNEL MODELS

A. PHY Model and MIMO Schemes

The total bandwidth of an OFDM system is divided into a series of sub-carriers, and each sub-carrier is subject to a flat fading narrowband channel. With proper coding and interleaving across frequencies, OFDM exploits frequency selectivity to its advantage as a source of diversity. Optionally, sub-sets of usable sub-carriers can be grouped into multiple sub-channels which are then allocated to different users for multiple access purposes – this is known as OFDMA. The key parameters, which are used in the simulation of the MIMO-OFDM PHY in this paper are the same as those in [5,6,7] and are shown in table 1.

Table 1 Parameters for the Proposed OFDM system

Operating Frequency	5 GHz
Bandwidth	100 MHz
FFT Size	1024
Useful Sub-carriers	768
Guard Interval Length	176
Sub-carrier Spacing	97.656 KHz
Useful Symbol Duration	10.24 μ s
Total Symbol Duration	12.00 μ s
Channel Coding	Punctured 1/2 rate convolutional code, constraint length 7, {133,171} _{octal}

In this paper a 2x2 architecture has been adopted and SM employs a linear MMSE detection scheme. In an OFDM system, a group of N_f low rate data streams are transmitted instead of a single high rate data stream. The normalized

channel capacity of a MIMO-OFDM system is given as [8]:

$$C = \frac{1}{N_f} \sum_{f=1}^{N_f} \log_2 \left(\det \left(I_{N_r} + \frac{SNR}{N_t} H(f) H(f)^H \right) \right) \quad (1)$$

$$= \frac{1}{N_f} \sum_{f=1}^{N_f} \sum_{n=1}^N \log_2 \left(1 + \frac{SNR}{N_t} \lambda_n \right)$$

where f is the number of sub-carrier, N_t , N_r is the number of transmit and receive antennas respectively, N is $\min(N_t, N_r)$, λ is the eigenvalue of HH^H , and $(\cdot)^H$ denotes the Hermitian function. The determinant of the channel H matrix (independent of the received signal-to-noise ratio (SNR)), is given by $\det(H(f)H(f)^H)$ [9].

B. Channel Model

The proposed system is evaluated using 2-transmit, 2-receive antenna MIMO channel data from deterministic, ray traced simulated channel models. The model uses a site-specific multi-element ray tracing model that is capable of supporting a wide range of propagation mechanisms [10]. The outdoor ray tracing trial consists of a base station located on a building top (23m above ground level), and a grid of possible mobile station locations covering an area of 400mx400m (1.7m above ground). The base station uses 2 patch elements (20 λ spacing). The mobile station uses 2 monopole elements (0.6 λ spacing).

The system is also simulated using a statistical channel model, and the performance result is used as a reference for the system operating in the realistic urban environment. The statistical model [11] represents a typical large environment for NLOS conditions and 250ns average rms delay spread. In order to verify the proposed LA algorithm in channels with different degrees of correlation, one uncorrelated and three correlated statistical channels are generated by applying three different correlation covariance matrices to the uncorrelated statistical channel, and the average H matrix determinant values across all channel realizations of these correlated channels are 0.5, 0.75 and 1 respectively. The correlation covariance matrix can be generated using either the traditional approach [12] used in this paper or a simple method [13] for simulation purposes.

Both the ray tracing and statistical channels are assumed to be quasi-static.

C. Adaptive MIMO OFDM

For the system considered in this paper, there are 6 AMC options [7], as shown in table 2.

Table 2 Transmission Modes and Data Rates

Mode	Modulation	Coding Rate	Coded Bits (subcarrier)	Max. Data Rate (R) Mbps (STBC / SM)
1	BPSK	$\frac{1}{2}$	1	32 / 64
2	QPSK	$\frac{1}{2}$	2	64 / 128
3	QPSK	$\frac{3}{4}$	2	96 / 192
4	16 QAM	$\frac{1}{2}$	4	128 / 256
5	16QAM	$\frac{3}{4}$	4	192 / 384
6	64 QAM	$\frac{3}{4}$	6	288 / 576

If exact prior knowledge of PER is available at the transmitter for all transmission modes for the current channel, optimal link adaptation can be achieved. However, since this is

not possible in reality, an algorithm capable of achieving near-optimal mode selection given only channel knowledge about SNR and H matrix determinant (LASD-F) was proposed in [5]. The propagation modelling employed offers a highly flexible method of evaluating channel parameters in detail. In this paper, a new route with more dynamic channel conditions is selected to present a further analysis on the performance of the LASD-F, LAS and optimal LA algorithms. An improved version of SNR and H matrix determinant based LA algorithm, LASD-V, which has no fixed threshold level and offers a further improvement on throughput by adopting a dynamic mode based look-up mechanism, is also proposed in the following section and evaluated later in the paper.

III. PHY PERFORMANCE ANALYSIS

Using the ray tracing model, complex MIMO channel impulse response data is derived on a point-to-multipoint basis for the entire area under consideration. From this data, the received SNR, H matrix determinant and theoretical capacity are determined for the entire area. The result for SNR is illustrated in fig. 1. By combining the channel data with a baseband PHY simulation tool, PER and throughput across the environment can also be determined.

The original SNR and H matrix determinant based sub-optimal LA algorithm proposed in [5] was derived after analyzing the results of the optimal LA performance analysis of predetermined route 1 (marked as line 1 in fig. 1). In this paper, route 2 (marked as line 2 in fig. 1), which covers location points experiencing more rapid changing channel conditions but medium SNR (thus presenting a more challenging Link Adaptation problem), is selected to further examine the performance of the various LA algorithms.

A. Optimal Link Adaptation and Sub-optimal Link Adaptation based on SNR only and both SNR and H Matrix Determinant with Fixed Threshold Levels

Optimal LA: In order to compare the throughput performance of various sub-optimal LA algorithms with the ideal adaptive system, the throughput achieved by an optimal LA algorithm for route 2 is determined and presented in fig. 2, given knowledge of PER as a function of location. The optimal LA aims at achieving the best possible throughput by choosing the combination of MIMO, modulation and coding schemes which are able to support the maximum instantaneous data rate.

LAS: To obtain the throughput performance of an SNR-only based sub-optimal LA algorithm (LAS), a prediction of the PHY mode with the highest throughput for every SNR can be obtained via a look-up mechanism shown in fig. 3(a). The degradation in throughput performance becomes more severe for route 2 than route 1 (results shown in [5]), as expected. This is because SNR is a dominant channel parameter for throughput performance in either the high SNR case (for which SM should be used) or the low SNR case (for which STBC should be used) but not the only important factor in the medium SNR region. Since route 2 mainly experiences medium SNR compared to route 1, SM is also sensitive to correlation level in the MIMO channels as well as SNR but this issue is neglected by the LAS approach.

LASD-F: Compared to STBC, SM is much more sensitive to the correlation level of the MIMO channels. To improve the performance of the sub-optimal LA, an SNR and H matrix determinant based LA algorithm assigning the same H matrix determinant threshold level to every SM mode (*LASD-F*) was proposed in [5] and is shown in table 3. In order to meet the error performance requirement for specific real time applications, the level of PER can be constrained by adjusting the threshold level of the H matrix determinant at the step 3 of the algorithm, because a high PER most commonly results from selecting a high throughput mode when the MIMO channels are correlated. The threshold level is selected in an increasing order at 0.5, 0.75 and 1 respectively, and they are set to be the same for all SM PHY modes. The performance of the *LASD-F* is proven to be much better than *LAS*, and as the threshold level increases from 0.5 to 1, the likelihood of severe PER is decreased as shown in fig. 3(b), (c) and (d). However, the consequence of increasing the threshold is that this algorithm becomes less sensitive to the frequent changing channel conditions resulting in more frequent occurrence of small throughput errors.

Table 3 *LASD-F* Algorithm

$\det(H(f)H(f)^H)$	Action		
<0.1	SNR look up table, STBC only		
0.1—Threshold Level	SNR look up table	STBC	No change
		SM	Reduce mode to the next lowest throughput
Threshold Level—2	SNR look up table, SM mode 6 cannot be used		
>2	SNR look up table		

B. Improved Link Adaptation Algorithm based on the Received SNR and H Matrix Determinant - Dynamic Look-up Table for Changing Channel Conditions

In order to further improve the throughput performance of *LASD-F*, instead of having a fixed threshold level, a new way to select the PHY mode is expected to be developed to meet the PER constraint and achieve the best possible data rate by effectively tracking the change of channel conditions at the same time.

Since the H matrix determinant threshold level of *LASD-F* implies the degree of sensitivity of the SM modes to the correlation level of the MIMO channels, it is important to know how much the throughput performance of the SM modes is affected by the level of H matrix determinant in order to improve the algorithm. By simulating SM-OFDM in 3 correlated statistical channels (introduced in part B of section II) with average H matrix determinant value ranging from 0.5 to 1, the link throughput results are generated based on the average PER results for every SM mode in every channel and the link throughput graph is present in fig. 4. As expected, the throughput curve shifts to the right as the average H matrix determinant value decreases. This result shows that the SM system in correlated MIMO channels requires a higher received SNR in order to achieve the same data rate for the case of the same system in uncorrelated MIMO channels. Using the link throughput result for the uncorrelated channel as a reference, the average amount of additional SNR required for every SM mode to compensate the diversity loss in the channels with

different degree of correlation represented by average H matrix determinant value is listed in table 4.

Table 4 Additional SNR Required for SM Modes in Correlated Channels to Achieve the Same Data Rate as the System in Uncorrelated Channels

Mode	Modulation	Coding	$\det(HH^H)=1$	$\det(HH^H)=0.75$	$\det(HH^H)=0.5$
1	BPSK	$\frac{1}{2}$	1.2 dB	2.0 dB	3.0 dB
2	QPSK	$\frac{1}{2}$	2.0 dB	3.0 dB	4.0 dB
3	QPSK	$\frac{3}{4}$	2.5 dB	3.5 dB	5.0 dB
4	16QAM	$\frac{1}{2}$	2.5 dB	3.5 dB	5.0 dB
5	16QAM	$\frac{3}{4}$	2.8 dB	3.8 dB	5.5 dB
6	64QAM	$\frac{3}{4}$	3.0 dB	4.1 dB	6.0 dB

According to the link throughput results of different SM modes in the correlated channels with the same level of H matrix determinant (have the same degree of correlation), the following conclusions are made:

1. Having the same modulation scheme, SM with stronger channel coding rate requires less additional SNR to achieve the same throughput result as in uncorrelated channels.
2. Having the same channel coding rate, SM with lower modulation scheme requires less additional SNR to achieve the same throughput result as in uncorrelated channels.

This is because as the modulation scheme supports more coded bits per sub-carrier, the minimum squared Euclidean distance between two codewords decreases, and therefore, the system becomes more sensitive to the correlation level of the MIMO channels [14]. One way to improve this situation is to adopt a stronger channel coding rate.

Based on the observation above, the throughput performance of *LASD-F* is expected to be further improved if the new algorithm treats the impact of the H matrix determinant on throughput performance differently for different modes instead of having a fixed threshold level for all SM modes. In order to choose the mode more accurately, the new algorithm is also expected to be able to target at every combination of SNR and H matrix determinant value rather than a range of values like the fixed look-up table in *LASD-F*.

In correlated channels, for an SM mode to achieve the same throughput performance as in uncorrelated channels, an additional amount of SNR is required to compensate for the diversity loss. Therefore, this SNR difference can be estimated using table 4 if the H matrix determinant value is known. Based on this calculated SNR difference and knowledge of actual SNR, a new ‘effective SNR’ taking into account both actual SNR and current channel correlation can be calculated. Therefore, the decision of the PHY mode depends only on this effective SNR value, and the SNR look-up table in the previous *LAS* can be used. Note that the additional SNR requirement is an estimate based on the analysis of statistical channel model performance and thus does not exploit any specific knowledge of the actual channel other than the H matrix determinant.

Fig. 3(e) shows the throughput performances of *LASD-V* algorithm. The results show that the new LA algorithm is able to control the error performance and track the changing channel conditions more effectively than *LASD-F* or *LAS*. The error performance of various LA algorithms can be illustrated in a statistical way. The throughput error can be obtained by calculating the absolute difference in throughput between the optimum and sub-optimum cases. The CDF, showing the

probability of operating below a certain throughput error level across route 2 is plotted in fig. 5. (note the discontinuous vertical axis). LAS system (equivalent to an H matrix determinant threshold level of 0) exhibits the worst performance. Using LASD-F, the adaptive system with lower fixed threshold level is able to choose the correct low data rate modes but is less reliable in choosing the higher data rate modes, and vice versa. The new LASD-V offers the best overall throughput performance. It reduces the worst case throughput errors by more than 150Mbps/s, which is more than 50Mbps/s better than LASD-F for the selected route 2. It also ensures correct mode selection for over 20% more locations than the LAS approach.

IV. CONCLUSIONS

This paper presents a further study of the LA algorithm based on SNR and H matrix determinant presented in [5]. By setting a suitable determinant threshold, the LA algorithm in [5] can significantly reduce the system failure rate and achieve good throughput performance compared to LA based on SNR only. It also works well in a medium SNR region, where the adaptive MIMO system frequently switches between SM and STBC mode based on the correlation level of the channels. One drawback of this algorithm, however, is that the threshold level is fixed for all SM modes, which results in a trade off between minimizing the delay by controlling the error performance and maximizing the data rate. LASD-F with a high threshold level offers a better control of the error level of the system throughput, but it is not particularly good at maximizing the adaptive system throughput performance by tracking the changing channel conditions, and vice versa. This is because for every SM mode, the threshold level is a single value and fixed, but the SNR level includes a range of values in the look-up table. Therefore, within the SNR range of one SM mode, the threshold level, as an average value, is most suitable for channels experiencing medium SNR in that range. The algorithm may underestimate the throughput performance if channels have a slightly lower H matrix determinant than the threshold level but a high SNR in the same mode range, or overestimate the performance if channels experience higher H matrix determinant but a low SNR.

This paper also proposes a new improved version of the SNR and H matrix determinant based LA algorithm, which offers better throughput and error performance. Throughput results show that SM PHY modes with higher modulation or weaker channel coding rates are more sensitive to correlation level of the MIMO channels, and therefore result in more throughput degradation compared to those modes with lower modulation or stronger channel coding rate. Based on this observation, the LASD-V algorithm modifies the SNR thresholds according to the observed determinant on a mode-by-mode basis for every combination of SNR and H matrix determinant and thereby offers a further performance improvement in terms of both reducing the locations in which severe throughput error is experienced and also reducing the number of locations in which any error occurs at all.

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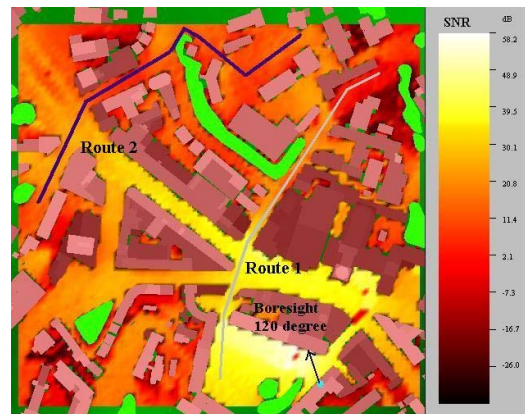


Fig. 1 Received SNR with 30dBm Transmit Power

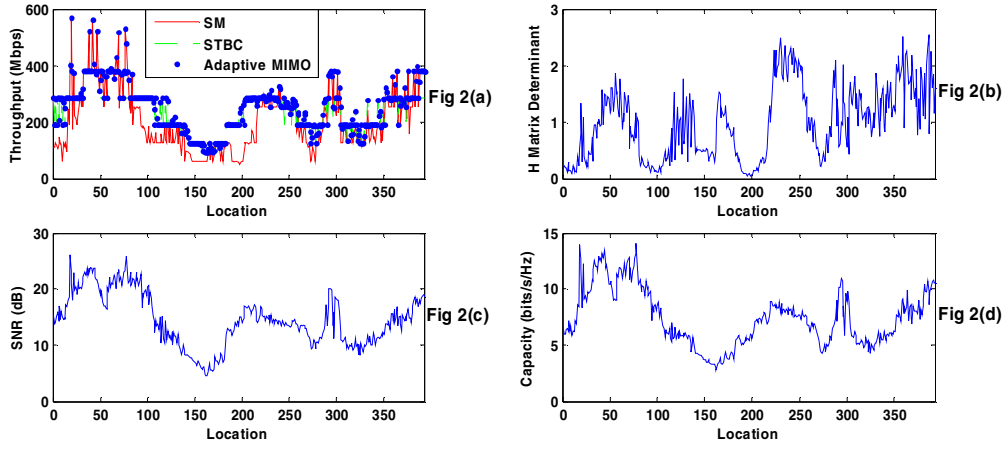


Fig. 2 Channel Statistics of the Route 2 with 30dBm transmit power: (a) SM/STBC/Adaptive MIMO Throughput (Mbps), (b) Determinant, (c) Received SNR (dB), (d) Capacity (bits/s/Hz) vs. Location points respectively

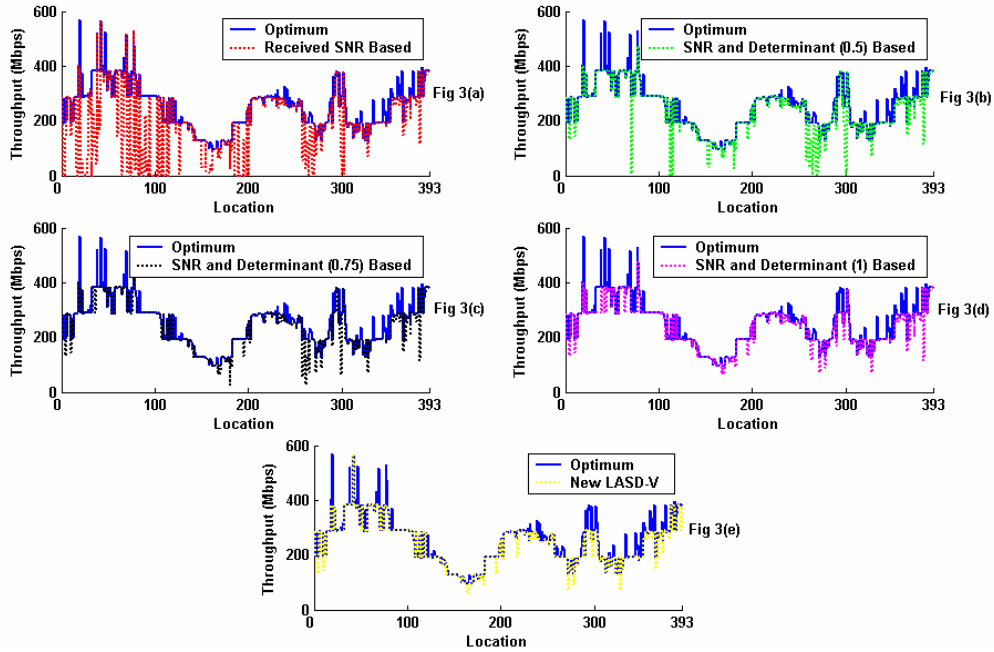


Fig. 3 Throughput Comparison for Route 2 between the Optimum and (a) Received SNR (b, c, d) Received SNR and H Matrix Determinant (Threshold Level at 0.5, 0.75 and 1) (e) LASD-V Algorithm Based System

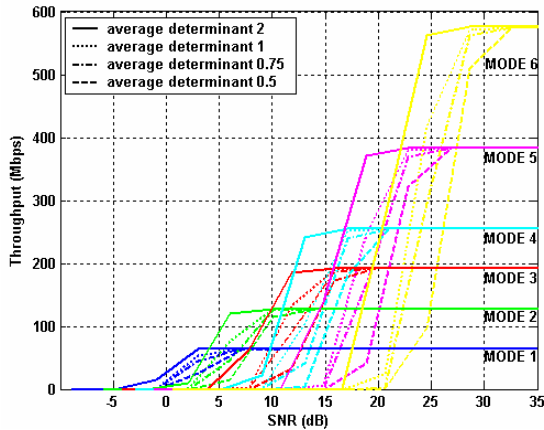


Fig. 4 Link Throughput Results for SM Modes in Statistical Channel Model with Average H Matrix Determinant Level at 0.5, 0.75, 1 and 2 Respectively

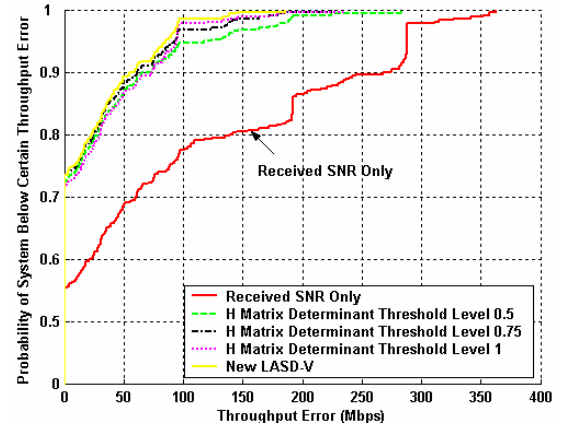


Fig. 5 CDF Probability of the Adaptive System Performance below Certain Throughput Error Level